EVAPORATION

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Summary

Evaporation in Nature is one of the main components of the global water cycle and it is the only means of water vapor transport from land and ocean to the atmosphere. From the physical point of view, evaporation is the result of two interacting processes, i.e. take-off of quickly moving molecules from the surface of water, snow, ice, soil, droplets and crystals in the atmosphere, and return of water vapor molecules above the evaporating surface back to liquid or solid state. Phase conversion from one state into another state is accompanied by absorption or discharge of heat. In general, distinction is made between evaporation from a water surface, evaporation from soil surface (direct physical evaporation), evaporation from the surface of plants (transpiration), and total evaporation (or evapotranspiration) which includes both physical evaporation and transpiration.

The very first attempts to describe evaporation were made in the seventeenth century. Recently, basic specific features of natural evaporation were established and a number of effective methods for computation of evaporation from different underlying surfaces were developed. The main instrument for measurement of evaporation is the evaporimeter—a tank with a fixed evaporating surface and depth, filled by some natural substance from which it is desired to estimate evaporation. The value of evaporation for a fixed time interval is estimated as a change in water volume in the evaporimeter.

Among the methods for evaporation measurement, the water balance method, methods of heat balance and turbulent diffusion, empirical methods and complex schemes are most often applied. The latter are based on joint solution of water and heat balances equations, initially with estimation of potential evaporation, followed by real evaporation. A specific type of evaporation is that from plants, which depends not only on meteorological conditions but also on the physiological properties of the plant.

1. Introduction

Evaporation in Nature is one of the main components of the global water cycle and it is the only means of water vapor transport from land and ocean to the atmosphere. As much heat is absorbed during conversion of water into vapor, evaporation is also an important factor of heat exchange on the Earth's surface. The particular importance of evaporation as a geographic process lies in the fact that characteristics of evaporation rate are included into the fundamental equations of water and heat balances for the underlying surface, thus establishing a direct relationship between water exchange and heat exchange processes. Evaporation in Nature depends on many factors, the most important of which are moisture content in the underlying surface and meteorological conditions above the surface. Meteorological conditions comprise solar radiation intensity, air humidity and wind velocity. From the position of the molecular-kinetic theory, evaporation is the result of two interacting processes, i.e. take-off of quickly moving molecules from the surface of water, snow, ice, soil, droplets and crystals in the atmosphere, and return of some water vapor molecules, above the evaporating surface, back to liquid or solid state. Rise of temperature of the evaporating surface results in a higher rate of water molecule take-off and their transport to the atmosphere as water vapor. Accordingly, the evaporation rate increases, too. On the other hand, a higher water vapor concentration above the evaporating surface increases the volume of the returning molecules. In this case, evaporation rate decreases. During the description of water evaporation in Nature, the different stages of the process are often separated. If water on the surface is in its liquid state and rises to the atmosphere as water vapor, this stage is termed 'evaporation'. If the quantity of molecules coming to the underlying surface exceeds the quantity transported to the atmosphere (e.g. observed during dew formation), this stage is termed 'condensation'. If evaporation takes place directly from the surface of frozen water (e.g. a process of direct conversion of water molecules from a solid state to a gaseous state), and, vice versa on cooling from a gaseous state to solid without apparent liquefaction, it is termed 'sublimation'. Phase conversion from one state to another is accompanied by absorption or discharge of heat. For example, evaporation of a unit of water mass, i.e. liquid water conversion into gas is accompanied by heat absorption:

$$L_E = (25 - 0,027\theta)\cdot 10^5 \qquad (1)$$

L_E is specific heat of evaporation in Joule/kg – the quantity of heat required to evaporate 1 kg of water; θ is the temperature of the evaporating surface, in ºC. A phase conversion of water directly from a solid to a gaseous state (sublimation) is accompanied by absorption of additional heat corresponding to heat loss for melting. Specific heat of melting a unit of distilled water mass at 0 ºC L_m equals $33.5 \cdot x\ 10^4$

Joule/kg. Water freezing and condensation are accompanied by equivalent heat discharge.

2. Background

The great variety of global landscapes (geotopes), each with characteristic features of evaporation, explain different methodological approaches to the study of evaporation. In general, we can distinguish evaporation from a water surface, evaporation direct from the soil surface (physical evaporation), evaporation from the surface of plants (transpiration), and total evaporation (or evapotranspiration), which comprises both physical evaporation and transpiration. There is also a term “evaporativity” (or potential evapotranspiration) which is evaporation from an optimally wet land area with constant compensation of water loss in soil. Also, depending on the research objective, it is possible to separate background evaporation (mean weighted over area) and evaporation from particular surfaces, i.e. from water, snow, agricultural field, forest, swamp, meadow, etc. The very first attempts to describe evaporation were made in the seventeenth century. Edmund Halley during his experiments proved that water circulation in Nature was closely connected with evaporation. After Halley, the first measurements of evaporation were made by D. Dobson who observed evaporation from a water surface in the vicinity of Liverpool from 1772 to 1775, from which he estimated monthly and annual evaporation. G.W. Rickman contributed much to development of evaporation theory and developed several new designs of evaporation pans for laboratory experiments. He studied the dependence of evaporation and condensation on the difference between air and water temperatures and some other factors. The first mathematical description of evaporation was made by John Dalton in 1802, and is known as Dalton’s law. According to Dalton’s low, the rate of evaporation to a free atmosphere is estimated by the following formula:

$$E = a(e_0 - e) \qquad (2)$$

where: α is a coefficient which depends on different factors not taken into account and affecting evaporation rate; e_0 - is the viscosity of saturated water vapor; e - is actual water vapor viscosity. Dalton’s law is valid for open water surfaces. Later, great contributions to the study of evaporation from a water surface, based on analysis of turbulent water vapor diffusion to the atmosphere and on analysis of heat balance, were made by Jeffreys, Leichtmann, Svedrup, Montgomery, Schmidt, Shuleikin, and others (see more details in *Evaporation from Open water Surface and Groundwater*).

It is more difficult to estimate specific features of evaporation from land. Basic physical principles of this process were developed late in the nineteenth and early in the twentieth centuries. The very first studies in this field were aimed at development of methods for measurements and computation of evapotranspiration (evaporation from soil plus transpiration from plants). During the second half of the twentieth century several designs of soil evaporimeters were prepared; they were separated into three types, i.e. evaporimeters with extreme wetting, evaporimeters with isolated monolith without additional wetting, and evaporimeters with screens. Evaporimeters of the first type included the evaporimeter of Dorandt, an earth-filled metal cylinder with a connecting tube put into a tank with water. The second type of evaporimeters was designed by M.A. Rykachev in 1898, and the third type of evaporimeter was developed by V.I. Popov in 1928. In some hydrological studies early in the twentieth century a water balance method was suggested to estimate evapotranspiration from large territories. This method was used to prepare maps of mean annual evaporation for the USA, European territory of the former Soviet Union, and other regions. Simple empirical graphs and formulas for estimation of evapotranspiration were widely used that time; they were based on the ratios between evaporation and different meteorological factors. These were the graphs of Meyer (1928), Kuzin (1934), formulas of Rykachev (1925), Blaney and Morin (1942), and others. Lack of any serious physical substantiation of this approach resulted in large errors in evaporation measurements when empirical schemes were applied. Theoretical methods for estimation of evaporation from land surface were first developed in the middle of the twentieth century, much later than the methods for computation of evaporation from a free water surface. Thornthwaite and Holzmann (1939) took the idea of Schmidt about evaporation measurement of a vertical turbulent flux of water vapor above an underlying surface and derived a formula to calculate evaporation rate based on measurements of specific air humidity and wind velocity at two elevations. This was a prototype of the present formulas based on the account of water vapor diffusion in the turbulent atmosphere.

Calculation of evaporation by the heat balance method was described in publications of Skvortsov (1928), Albrecht (1942) and others. Another research trend to study evaporation from land was connected with studies of the effect of different factors on evaporation from soil and on transpiration of plants. At the end of the nineteenth century numerous qualitative relations between evaporation rate from soil and physical and mechanical soil properties, plant cover and some meteorological factors were established. The discovery of three stages of evaporation made by the Russian pedologist P.S. Kossovich (1904) was a great achievement in studying specific features of evaporation from soil. He established that when soil saturated with moisture began to dry, the rate of evaporation is about constant at some time (stage 1). Then, at a certain soil moisture content, the rate of evaporation trends to a rapid decrease to a relatively low value (stage 2). After this, the evaporation rate decreases slowly until complete desiccation of the soil (stage 3). The conclusion made by Kossovich were later proved by the English agrophysicists Kean (1914) and Fisher (1923), as well as by numerous experiments. In the nineteenth century the concept of transpiration coefficient for a plant was introduced; it included the ratio between water weight lost in transpiration and increment of dry matter weight for a specified time interval. It was first assumed that the transpiration coefficients for similar plant species were more or less constant. This concept was refuted early in the twentieth century by Brigs and Schantz and by other scientists who established the considerable variability of transpiration coefficients during variable meteorological conditions. This confirmed the idea of K.A. Timiriazev who had noted early in the 1890s that water loss for transpiration in usual conditions greatly exceeded the actual water requirements for plants and it was more a physical evil than a necessary physiological demand of the plant. Livingstone made an attempt to establish relations between the rate of evaporation from the leaves of plants and rate of evaporation from an evaporimeter. As a result of his experiments, Livingstone discovered that the ratio between evaporation rate from plants and evaporation from the evaporimeter (under similar meteorological conditions) varied greatly depending on the state of the plant and on environmental factors. These changes were explained by

Livingstone by the mechanism of opening and closing of stomata (small pores in the surface of leaves) under the influence of drying of leaves, if evaporation was intensive. Livingstone's studies were later continued by Walter. Some hydrologists tried to discover empirical dependences of water loss for transpiration of different vegetative cover upon a season, and tried to estimate mean total water loss for transpiration for the whole vegetative period (Meyer et al.). These quantitative assessments were quite approximate because they were obtained on the basis of using methods for transpiration measurements which were not satisfactory from the physical viewpoint. The results of present geophysical studies of evaporation under natural conditions (to be discussed below) made it possible to establish basic specific features of natural evaporation and to develop a number of effective methods for computation of evaporation from different underlying surfaces. Meanwhile, it should be noted that despite the progress in this field, the available methods for computation of evaporation are less accurate than methods for computation of the other main water balance components (precipitation and runoff).

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Biographical Sketches

Anatoly Vershinin was born in Russia in 1941. He graduated from Department of Climatology, St. Petersburg State University. In 1974 he was awarded a Doctor of Technical Science, and in 1996, Docent, St. Petersburg State University.

The positions he has held are Principal scientist (1976-1990), State Hydrological Institute; Scientific secretary (1971-1980), Hydrology Commission of Geographic Society of the USSR; Associate Director of Ecological Research (1990-1992), “Ecology”Scientific and Industrial Corporation; Deputy Director for Science (1992-1996), Northwest Branch of Water Resources Institute; Docent (1996-present), St.Petersburg State University.

His international experience includes membership (1983-1990) of the Working Group on Soviet Economic Mutual Aid on the problem of “Influence of Human Activity on Water Resources”. He has also worked as WMO Expert (1983-1991), on Hydrological and Meteorological problems in Syria and Mongolia.

His lecturing activities include courses in St. Petersburg University on Meteorology, Climatology, Microclimatology, Ecological Problems in Meteorology, and, at St. Petersburg Hydrometeorological University, Reclamation Hydrology.

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He has had more than 70 publications in numerous national and international journals and proceedings of conferences and symposia, and has written the following books:

Water and Salt balance on reclaimed areas in South Kazakhstan, 1980, Co-authors: S.Kharchenco, K. Tsytsenko et al, Leningrad, Gidrometeoizdat (in Russian);

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"Methodology for distinguishing between man's influence and climatic effects on the hydrological cycle", 1989, co-author, Technical Documents in Hydrology, UNESCO;
"Casebook of Operational Hydrological Networks in RA-VI (Europe)",1995, WMO;

"Basis of Geoecology" , 1994, Co-author, St. Petersburg University (in Russian).